

## MAUNA LOA OBSERVATORY: THE FIRST FIVE YEARS

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### ABSTRACT

Weather Bureau Research Station, Mauna Loa Observatory (MLO), at an elevation of 11,150 ft. on the north slope of Mauna Loa, Hawaii, was dedicated in July 1956 and assigned a permanent staff one year later, in preparation for the International Geophysical Year.

The historical background, physical setting, and facilities of the Observatory are described and the many and diverse scientific uses made of the site in the nearly six years of its existence reviewed. MLO's present effort lies principally in the continuous monitoring of solar radiation, carbon dioxide, total and surface ozone, and the meteorological elements, and in the analysis and interpretation of the data. Ice nucleus counts have been made during local volcanic eruptions and for other periods ranging from several weeks to a year or more. An extensive program in atmospheric electricity was recently completed. The motions and properties of the atmospheric envelope about Mauna Loa are being explored as a key to interpreting the observations made within it.

The Observatory's major advantages for a variety of studies in the geophysical and space sciences lie in its elevation, its freedom—due to the underlying trade inversion—from most of the water vapor and other turbidity of the lower troposphere, and the consequent exceptional transparency of the overlying atmosphere. It offers, in addition, an equable climate the year around and a base station for work done at the summit of Mauna Loa, 2500 ft. above.

More important than any of the foregoing, however, may be MLO's possession of an atmospheric environment that has little prospect of debasement through the encroachment of population or industry. This endowment makes the Observatory of inestimable value as a vantage point from which to maintain a careful surveillance of the significant indices of global atmospheric change.

### 1. INTRODUCTION

#### THE HISTORICAL BACKGROUND

It seems especially appropriate that a collection of papers dedicated to Dr. Harry Wexler should include this account of an enterprise so intimately associated with him.

The potential value of a high-altitude geophysical observatory in the oceanic Tropics had long been realized. The uniqueness conferred on Mauna Loa by its height, insularity, and mildness of climate even at high elevations; its distance from sources of industrial pollution, yet accessibility from large cities; and its freedom (due to the trade inversion) from much of the water vapor and debris of the lower atmosphere, was recognized by the First Pan-Pacific Science Congress which, in 1921, adopted a resolution calling for the establishment of a weather station at the summit. But it was not until 1950 that a cinder road across the lava wastes opened the upper mountain to motor vehicles and made an observing station there feasible.

In December 1951 a small hut was constructed at an elevation of 13,400 ft. (1/4 mile from and 280 ft. below the summit) to house recorders for the meteorological elements and to provide shelter for scientific parties. Building and equipment were admittedly crude, and were regarded only as a first step toward a manned observatory. From these early observations, supplemented by others along the slope, the first quantitative portrait of the mountain climate began to emerge [24].

In June 1956, in cooperation with the National Bureau of Standards, the Weather Bureau erected at 11,150 ft. a much larger building containing working and living quarters for visiting scientists. To distinguish it from the summit hut, it was designated the *slope unit* of Mauna Loa Observatory [10, 11], but soon came to be called simply Mauna Loa Observatory or, as it will often be referred to in this paper, MLO.<sup>1</sup> With the assignment to MLO of an important role in the International Geophysical

<sup>1</sup> In January 1963 MLO became a Weather Bureau Research Station: WBRS, MLO



FIGURE 1.—Dr. Harry Wexler and colleagues on a visit to Mauna Loa Observatory during the IGY. From left to right, Dr. Wexler, then chief scientist for the U.S.-IGY Antarctic Program; Alan Shapley, vice chairman, U.S.-IGY National Committee; Dr. Lloyd Berkner, past president of ICSU; Dr. John Tuzo Wilson, then president of IUGG; and Dr. Thomas O. Jones of the National Science Foundation. On the right, Jack C. Pales, physicist-in-charge, Mauna Loa Observatory. Photo courtesy of Larry Kadooka, *Hilo Tribune-Herald*.

Year [12], a Weather Bureau staff was stationed there, and the long-awaited permanent observatory was made a reality.

It scarcely need be pointed out that undertakings of this sort do not come into being unassisted, but only through the willing and skillful good offices of many a midwife. Thus, MLO owes much to Dr. Robert H. Simpson who, when he was Meteorologist-in-Charge of the Weather Bureau's Pacific Supervisory Office, Honolulu, and afterwards, endeavored unremittingly to bring it into existence; to his successors at Honolulu, Gordon D. Cartwright and Roy L. Fox, who devoted much time and effort to the same end; to Ralph Stair and the National Bureau of Standards for their cooperation in constructing the main Observatory building; and to Dr. Harry Wexler, for his unstinting encouragement and support.

The Observatory staff reported directly to Dr. Wexler; and although MLO was but one of his many responsibilities as Director of Meteorological Research, he gave it always a special measure of his interest and attention, and helped see to its continued existence. He visited the Observatory often, for Honolulu was a way station between Washington and the many destinations to which his activities took him; and he seldom failed, despite the press of other business, to leave time for the flight to Hilo and the drive to MLO (fig. 1). He took intense pleasure in the ecology of the lush rain forest, and found in the bizarre landscape of the upper mountain, on which the Observatory was the only reminder of the world below, renewed confidence in the promise of so remote yet accessible a site.

As he foresaw, the years have brought a wide and

increasing use of MLO's facilities and data and a growing awareness of its potentialities. In view of this and of the many inquiries concerning matters not adequately covered in their earlier account prepared less than two years after the Observatory opened [26], the authors had been planning a revision to enlarge the treatment of certain topics on which information was not then available and to summarize later developments.

They deeply appreciate the opportunity to do so at this time and in this volume.

#### THE LOCALE

*Physical Setting.*—Mauna Loa (Long Mountain) is situated on the island of Hawaii, largest and southernmost of the Hawaiian group (fig. 2). At  $19^{\circ} 30' N.$  latitude, it lies well within the geographic Tropics, more than 2,000 mi. from the nearest continental land mass, and in the midst of an equable ocean which, in that vicinity, has a mean annual temperature of  $77^{\circ} F.$ , an annual range of  $4^{\circ} F.$ , and a daily range of less than  $2^{\circ} F.$  [39].

Measured from its roots on the ocean floor 18,000 ft. below sea level to its 13,680-ft. summit, Mauna Loa is the earth's greatest single mountain mass, and it is still an active volcano, with the symmetry and gradual slope (the average grade is 7 percent) of the fresh volcanic cone [32].

The prevailing wind near sea level is the east-north-easterly trade; and occurring with nearly the same frequency (about 75 percent for the year as a whole) is the associated trade inversion, whose average height of approximately 6,500 ft. is only half that of Mauna Loa itself and marks the mean timberline on its slopes. The mountain below the inversion is rainy (the island maximum exceeds 300 in. a year) and densely vegetated; the upper slopes are a wasteland of dark lava.

#### *Coordinates.*—

Elevation: 11,150 ft. (3398 m.)

Latitude:  $19^{\circ} 32' N.$

Longitude:  $155^{\circ} 35' W.$

Geomagnetic Latitude:  $19.9^{\circ} N.$

*Accessibility.*—The Observatory is a drive of 47 mi. and less than 2 hr. from Hilo, the largest city (population 25,000) on the island of Hawaii. The first 30 mi. of road are hard-surfaced; beyond, it is of crushed lava, and rough in places. Four-wheel drive vehicles are preferable and, for the additional 8 mi. to the summit, essential; the Observatory maintains several for its own needs.

Honolulu, a modern American city of 350,000 and the cultural, economic, and population center of the State, with research institutes, technical libraries, a large university (which includes the Hawaii Institute of Geophysics), and facilities for the purchase, fabrication, and repair of equipment, is an hour from Hilo by air, with frequent daily commercial flights.

#### FACILITIES

*Buildings.*—Mauna Loa Observatory lies within a

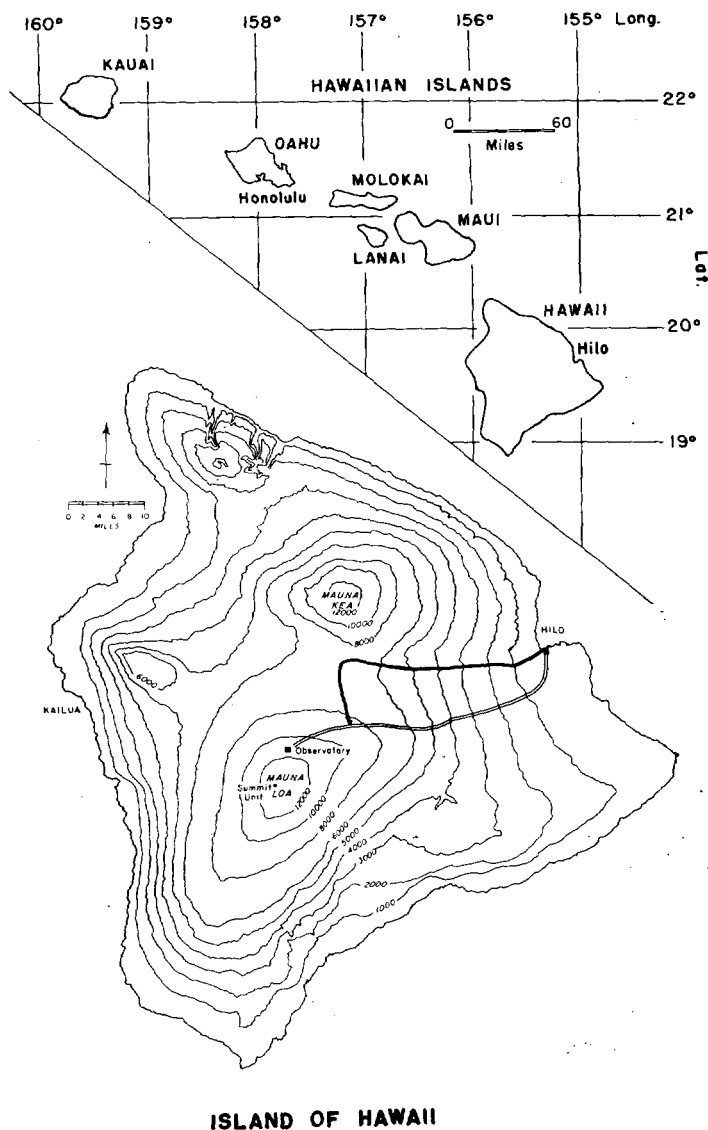


FIGURE 2.—Hawaiian Islands, showing the island of Hawaii and roads between Hilo and Mauna Loa Observatory.

leveled 4.05-acre plot on the gently sloping north face of Mauna Loa, surrounded by the vast and barren expanse of dark lava which composes the upper mountain (fig. 3).

The main building is a 20-by-40-ft. concrete block structure partitioned into working and living quarters. A concrete slab, 15 by 45 ft., along its south side provides an outdoor instrument platform. Auxiliary structures include housings for the Dobson spectrophotometer and other instruments; the generator shed; fuel and water tanks; and masts for the anemometers and for the carbon dioxide intakes.

The Observatory also maintains offices in Hilo together with an instrument shop, warehouse space, and other facilities in support of the mountain station.

*Electricity, Water, Communications.*—110-volt, single-phase, 60-cycle alternating current is provided by two

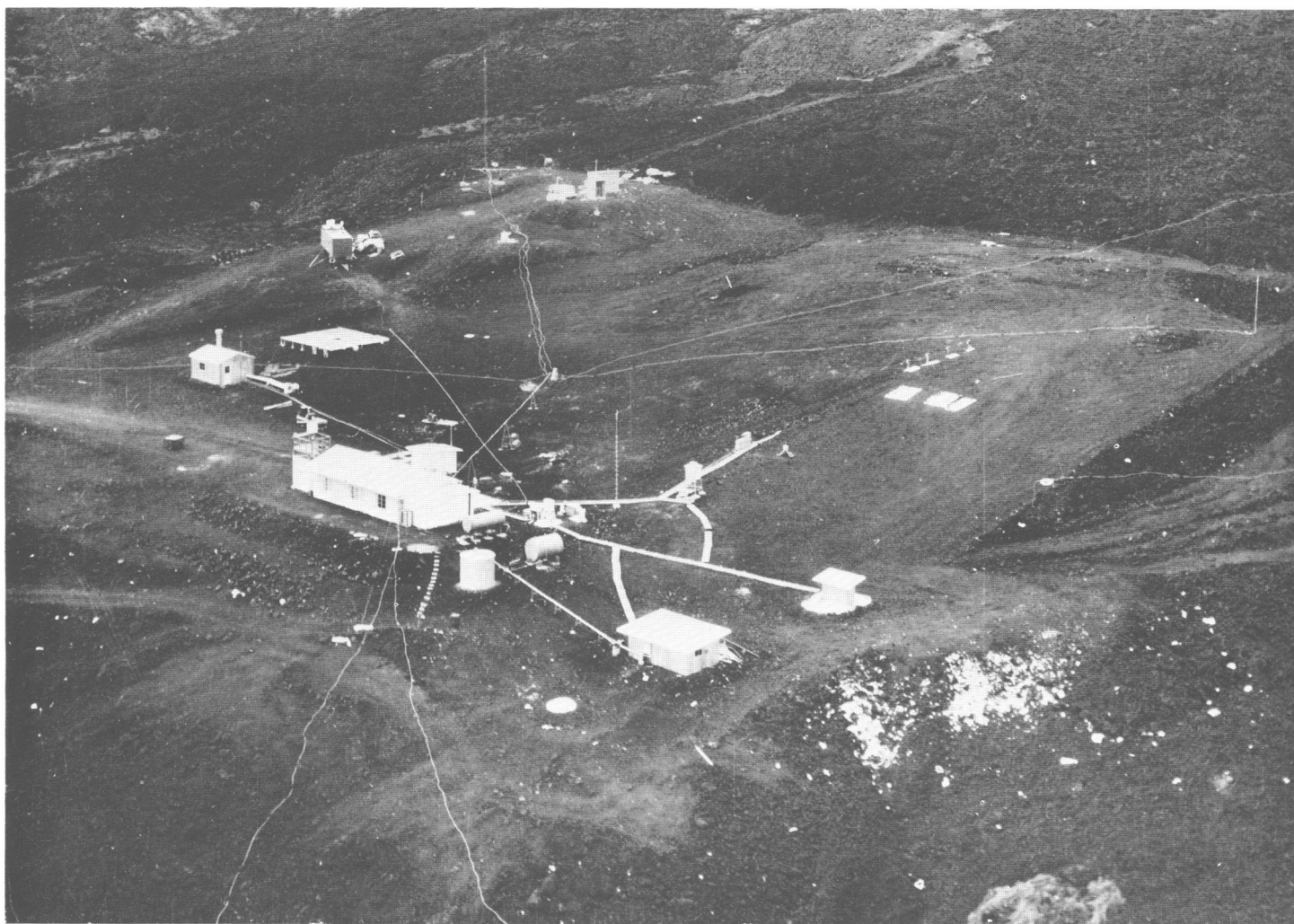


FIGURE 3.—Mauna Loa Observatory from the air, 1962. Dark background is loose cindery lava called aa, which predominates on the upper slopes. Brighter patches are of hard-surfaced pahoehoe lava. Light thin lines at right angles are aluminum tubing from CO<sub>2</sub> intakes to analyzer in main building.

35 kw. diesel generators. These are ordinarily used alternately to permit preventive maintenance and minimize power interruptions, but they can be synchronized to operate in unison. Frequency regulated current is supplied to the more critical circuits.

Water is obtained by draining roof rainfall into a 5,000-gallon tank. This is augmented, at times, by haulage from Hilo.

The Observatory is linked to its Hilo office and to the Hilo Weather Bureau station by radio and radio-telephone, and to its vehicles by 50-watt transceivers.

#### STAFF

Mauna Loa Observatory's present complement includes two physicists, several meteorological aides, an electronics technician, and a clerical assistant. Members of the scientific staff ordinarily spend several successive days at MLO on a rotating schedule, but reside in Hilo. Close collaboration is maintained with a small research unit at the Weather Bureau's Pacific Supervisory Office, in Honolulu.

## 2. WEATHER AND CLIMATE

In keeping with its tropical maritime locale, the Observatory has a mild climate for the altitude. Severe weather is infrequent and the rigors of Alpine life virtually unknown. On the contrary, the brilliant skies, intense insolation, moderate temperature, and low humidity, encountered in so unusual and remote a setting, induce in most visitors a feeling of exhilaration and well being.

#### THE MOUNTAIN CIRCULATION

Like other large mountains, Mauna Loa generates its own local climate and a circulation often at variance with that of the surrounding free air. The properties and motion of this atmospheric envelope exhibit marked diurnal variations, a characteristic of great intrinsic interest not simply for the weather and climate of mountains generally, or of Mauna Loa specifically, but also for the interpretation of the observations made at MLO—since, as will appear later, not only the common weather elements but also atmospheric electricity and the con-

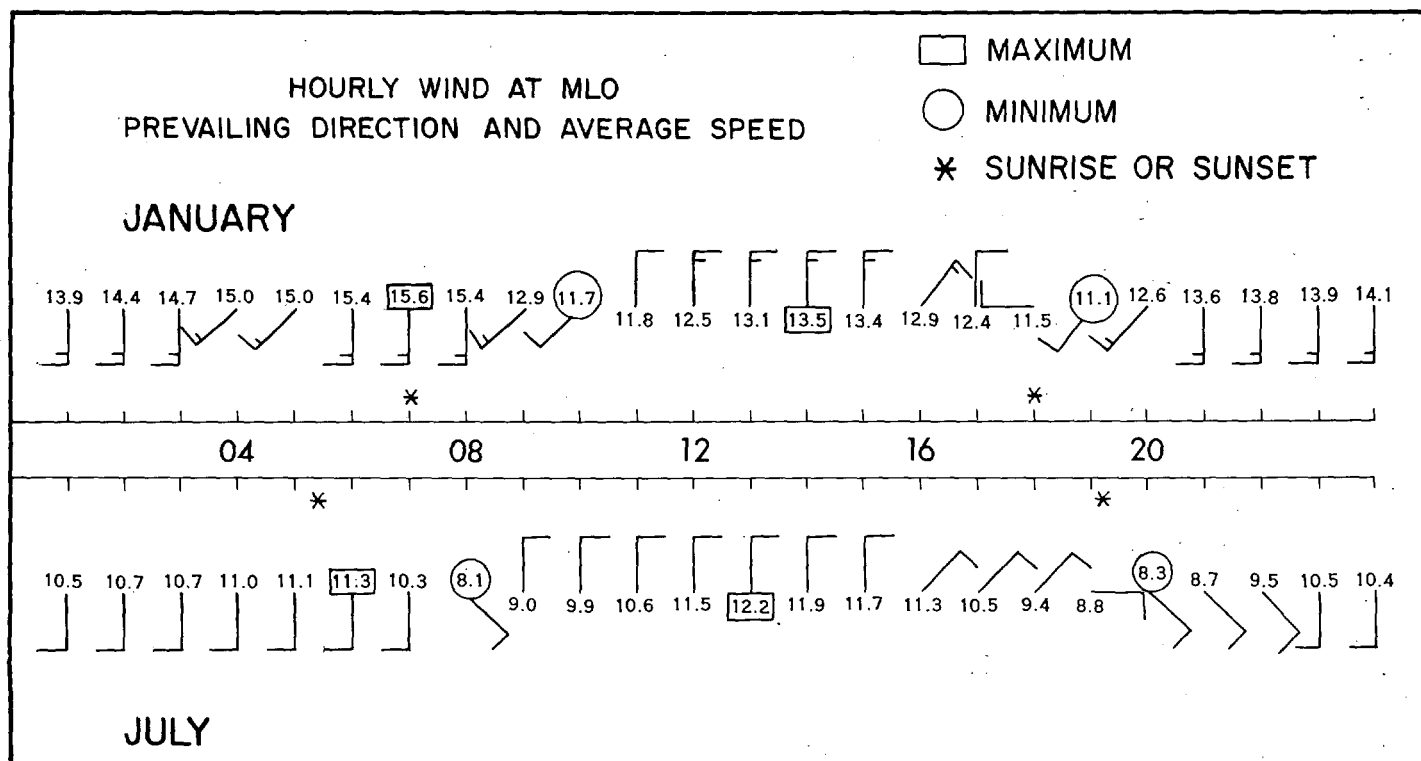


FIGURE 4.—Diurnal variation of the prevailing wind at Mauna Loa Observatory, January and July, 1958-62. Winds are lightest at transitions between upslope and downslope flows. Strongest nighttime winds occur near sunrise and minimum temperature; and the strongest daytime winds in mid-afternoon, when insolation is most intense and the ground temperatures highest.

centrations of carbon dioxide, surface ozone, and ice nuclei strongly reflect this diurnal cycle. Although data are still too sparse in time and space to permit these properties and motions to be delineated in detail, a schematic outline like the following may be offered.

During the night radiatively cooled dry air descends Mauna Loa, manifesting itself at MLO as a southerly wind (note the topographic gradients in fig. 2). With most of the tropospheric water vapor and turbidity confined beneath the trade inversion several thousand feet below the station, nights are typically clear, mornings brilliant, and insolation intense.

The downslope flow persists until after sunrise, when it is first disrupted by local convection and then replaced by the northerly daytime wind. Although the latter is commonly referred to as "upslope," air reaching the Observatory during the forenoon appears from its low humidity to have originated well above the inversion.

By early afternoon, however, distinctly moister air begins to arrive and may envelop the Observatory briefly in low cloud or light rain. Before evening the daytime winds begin to fail, the low clouds quickly dissipate, and sunset is soon followed by a resumption of the nocturnal downslope flow.

It is evident from the foregoing, that although the inversion may impede, clearly it need not prevent, the upslope transport of air; so that on Mauna Loa, as on

large mountains elsewhere, the local circulation dominates the diurnal aspects of climate.

Through turbulent exchange, mountains tend also to take on the properties of the surrounding free air. This is more pronounced at exposed summits than on slopes, and for seasonal than for diurnal factors. Thus Mauna Loa's climate fuses the influences of the mountain circulation, the free air, the continentality of its own bulk (128 sq. mi. of its surface are above 10,000 ft.) and the tropical maritime locale.

Against this background the salient features of the basic weather elements at MLO during about the past six years and for several earlier years at two nearby locations, 11,500 and 10,958 ft., will be reviewed.

#### WIND

The cardinal aspect of wind at MLO is its diurnal variation. The reversal from the nocturnal southerly (downslope) wind to the northerly (upslope) daytime wind is, in the mean, evident throughout the year (January and July are shown in fig. 4), and is in marked contrast with the nearby free air, whose motion exhibits little diurnal change.

That the mountain circulation is thermally driven is implied also by other details in figure 4. Thus, the reversals in wind direction follow soon after sunrise and sunset. Perhaps most indicative is that each 24-hr.



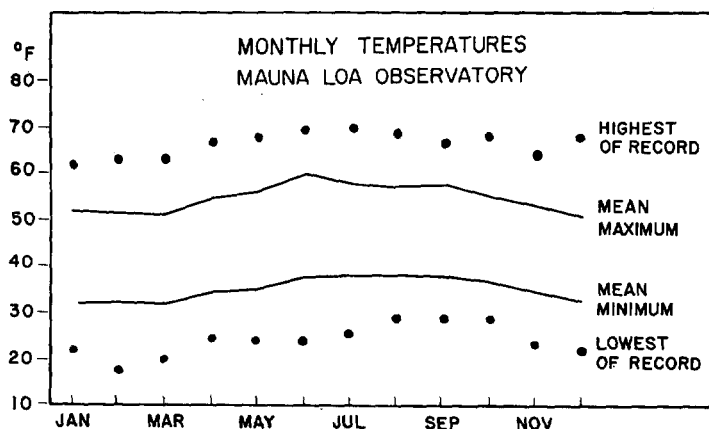


FIGURE 5.—Mean monthly maximum and minimum temperatures and highest and lowest of record during 8 years at or near Mauna Loa Observatory illustrate seasonality and the moderateness even of the extremes, for the altitude.

period contains a double maximum and double minimum in speed: the downslope flow increases steadily during the night, reaching its peak in early morning, just before sunrise triggers its decline; while the upslope wind is strongest in mid-afternoon, when insolation and slope temperatures are at their highest.

The lightest winds occur during the morning and evening transitions between upslope and downslope flow.

On the whole, winds at MLO are moderate. The highest recorded were the sustained speeds of 75 m.p.h. with gusts to 100 experienced in March 1958. These were not, however, topographically induced, but arose from the near approach of a well-developed cyclonic storm which brought unusually strong winds to the entire Hawaiian area. Again in January 1959 a similar event produced average winds of 80 m.p.h. and gusts exceeding 105.

As these two occurrences suggest, and as other data confirm, the strongest winds do tend to occur in winter and to reflect in all seasons the synoptic, rather than the local, flow.

#### TEMPERATURE

The annual march of temperature, and the highest and lowest of record in each month, are shown in figure 5. The moderateness, even of the extremes, is noteworthy. Thus the highest in about 10 yr. at MLO and its vicinity was 70° F. (June and July of 1958) and the lowest 18° F. (February 1962), while the average daily maximum for the warmest month is 60° F. and the average daily minimum for the coldest month, 32° F. The mean daily range is about 20° F.

The seasonality is predominantly marine and free air in character: the sharp spring rise to an early (June) maximum, the plateau to late summer, and the persistence of low temperatures through March. The diurnal range, on the other hand—large for the altitude and the oceanic Tropics—is attributable to the size of the upper mountain and to the radiative properties of its dark lava.

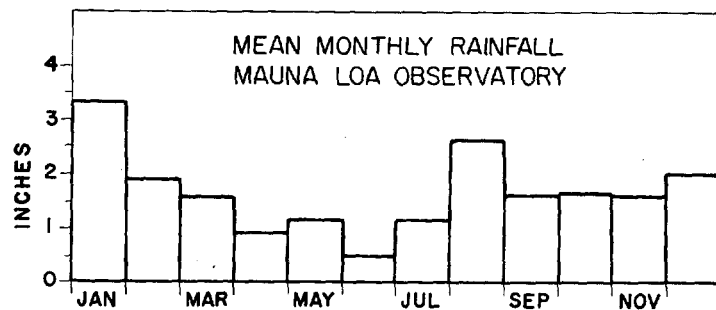


FIGURE 6.—Mean monthly rainfall at or near Mauna Loa Observatory (1956-62, incl.) peaks at the cyclonic rains of winter and the summer maximum in the frequency of upslope showers and easterly waves.

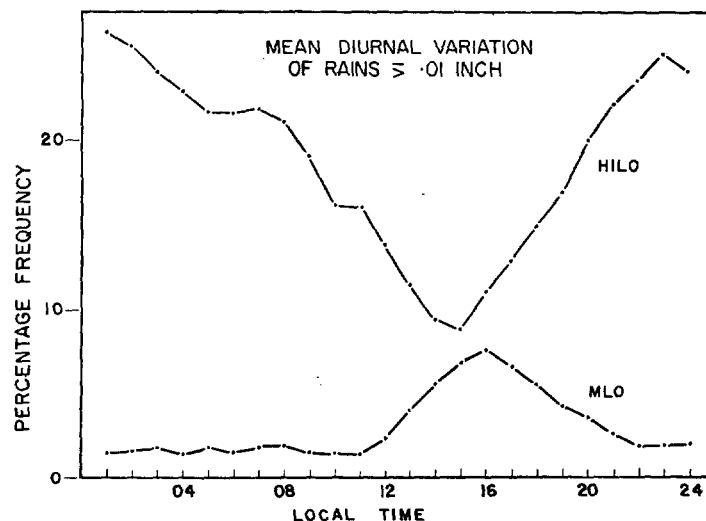


FIGURE 7.—Diurnal variation of rainfall frequency at Mauna Loa Observatory and Hilo (both for 1958-62, incl.). Hilo exhibits the nocturnal maximum typical of a maritime regime and windward Hawaii. In contrast the afternoon maximum at MLO reflects showers forming in the moist upslope flow.

#### RAINFALL

The chief source of rainfall in the Hawaiian Islands is orographic uplift of the moist trade wind. Particularly during the cooler half-year, this is complemented by frontal and cyclonic (including Kona storms) precipitation, and by convective showers in the island interiors and uplands.

Observations for 8 yr. at or near MLO are summarized in figure 6. The mean annual rainfall (approximately 20 in.) appears to be consistent with island-wide isohyetal charts based on longer records but, with only a single exception, on gages below 6,000 ft. Yearly totals ranged from about 10 in. (1962) to 37 in. (1956).

Although the record is still too short to justify seeking a seasonal trend, the intimation of a double maximum (fig. 6) is not incompatible with the greater frequency of cyclonic rains in winter and of local upslope showers on the upper mountain in summer, augmented in August by the heavier rainfall associated with easterly waves.

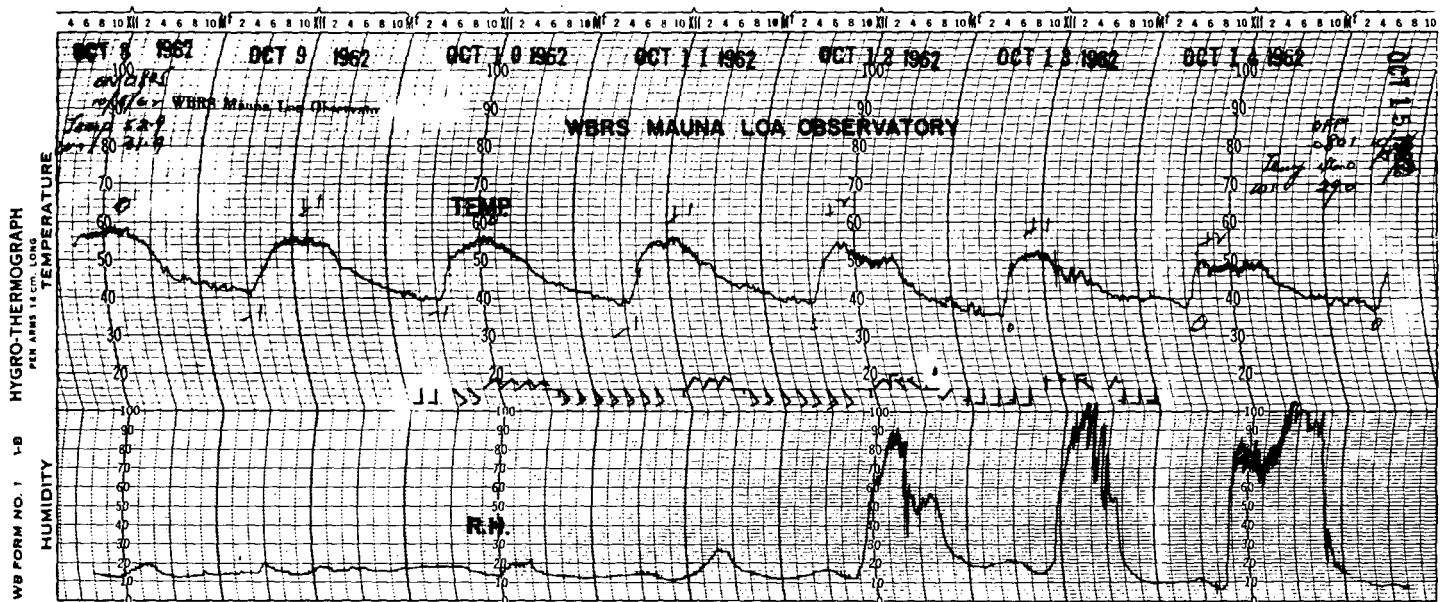


FIGURE 8.—Hygrothermograph trace for Mauna Loa Observatory, October 10–13, 1962, illustrates progressive development of the mountain circulation and the accompanying influx of moist air from lower elevations. The afternoon increase in relative humidity, barely discernible on October 10, is at its peak by October 13.

The wettest month was January 1956 with 12.89 in., but the variability of rainfall is indicated by the fact that four of the eight Januaries had less than half an inch.

The late afternoon maximum in rainfall frequency at MLO echoes again the formation of light showers within the moist upslope flow, and is in marked contrast with the nocturnal maritime maximum found in Hawaii at lower elevations exposed to the trades. (Compare MLO, for example, with Hilo, a much wetter station—about 145 in. per yr.—on the windward coast (fig. 7).)

#### HUMIDITY

The diurnal variation in the moisture content of the air at MLO constitutes perhaps the most striking demonstration of the mountain circulation and of the origin of the air reaching that station (fig. 8). The low nighttime humidity matches closely that of the ambient free air at the same elevation. Often the northerly wind of forenoon still retains the low dew points found above the inversion, and may thus represent chiefly inflow, rather than ascent. But beginning near noon the humidity increases, often quite abruptly, until it reaches values which, on the Hilo soundings, occur only in the marine air below the inversion. However, measurements of the total precipitable water above Mauna Loa [31] suggest that the afternoon rise may involve only a thin skin of moister air. With the decline of the upslope currents in late afternoon, the humidity at MLO drops as rapidly as it rose.

Exceptions to this diurnal cycle are chiefly of two extremes: in the absence of the trade inversion, the Observatory may remain for some time within a deep moist layer; or an unusually intense and low inversion may

inhibit the upslope flow and permit exceptionally dry conditions to persist at MLO throughout the day.

In October 1960 an infrared hygrometer [9] was put into use at the Observatory, primarily to explore with greater accuracy and detail these extended intervals of low humidity and the forenoon and early evening transition periods. An analysis of these data is currently in progress.

#### SKY COVER AND VISIBILITY

Cloud amount and its time variations are of central importance for many potential uses of a mountain station. Although based only on daylight observations, figure 9 clearly indicates both a diurnal and seasonal variation in

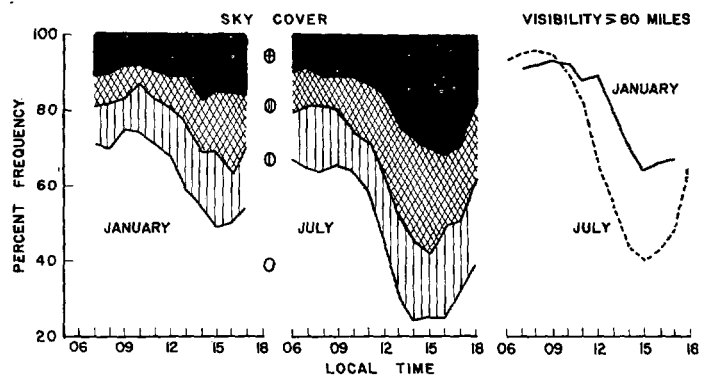


FIGURE 9.—Diurnal variation of sky cover and visibility at Mauna Loa Observatory (1958–62, incl.). Clear skies and good visibility are less frequent in afternoon because of fractocumuli-forming in the moist upslope flow, and in July because insolation and the mountain circulation are more intense then.

sky cover. The afternoon minimum in clear skies ensues largely from the formation of fractocumuli in the moist upslope wind; and the greater cloudiness of summer (than of winter) presumably from its greater isolation and correspondingly more intense upslope flow. Both seasons show an unmistakable tendency for clearing by early evening.

Since these compilations include even the most diaphanous clouds, they considerably *understate* the sunniness of the site and the frequency with which the solar disk may be seen; and it would appear from these and other data that about 90 percent of the nighttime and well over 50 percent of the daytime hours are nearly or entirely free from overlying cloud.

Perhaps because of its smooth terrain and gentle slope, Mauna Loa appears also to have fewer orographic cirrus than do the lower but more rugged topographic features of the other islands.

Excellent visibility ( $\sqrt{80}$  mi.) at MLO so closely parallels sky cover in frequency and in its physical basis that figure 9 is felt to require no further discussion.

#### SNOW

None of Hawaii's high mountains (Mauna Loa, Mauna Kea, Haleakala) is perennially snow-covered.

Snow is most frequent in the cooler half-year, but has also been seen in every other month. It is not, however, always clear whether a report is of freshly fallen snow or of one of the pockets which sometimes survive to midsummer. On one occasion snow was said to have extended down to 6,500 ft., but the ephemeral snow line of winter lies nearer 12,000 ft.

#### THUNDER, LIGHTNING, HAIL

Like other "severe" weather, thunderstorms at MLO are infrequent and relatively mild, but often accompanied by light hail. During 1958 to 1962, an average of nine occurred annually; and there appear to be seasonal peaks in late spring and early autumn. On several occasions an isolated thunderstorm or cumulonimbus tower has formed over Mauna Loa summit in the "chimney" of updrafts converging along its slopes.

### 3. SOME SCIENTIFIC USES, PAST AND PRESENT

In the more than five years since the opening of Mauna Loa Observatory, a number of persons and institutions have used its facilities or availed themselves of the elevation, atmospheric clarity, and low water vapor content, or some other attribute of the site. These studies are listed below with references to the agency or principal investigator and to published reports. Their diversity suggests the wide and continuing need for a high-altitude station in an environment as free as possible from the turbidity of the lower troposphere.

*The forms taken by snow crystals growing in a naturally aerosol-free environment* (micro-photographic analysis of

freshly fallen snowflakes at the summit of Mauna Loa), December 1956 to January 1957, Geophysical Research Directorate, Ukichiro Nakaya [21].

*Spectrographic observations of water vapor in the atmosphere of Mars* during the planet's close approach in July 1956 and of *Jupiter* in May 1957, National Geographic Society and National Bureau of Standards, C. C. Kiess [16].

*Atmospheric transmission in the infrared* (along a 17-mi. baseline between Mauna Kea and MLO) July to September 1957, Naval Research Laboratory, Harold W. Yates [36].

*Spectroradiometry of the sun* between 0.3 and 2.5 microns, June 1956 and May 1957, National Bureau of Standards, Ralph Stair [31].

*Lunar occultation program* (to connect the Hawaiian Islands with the North American geodetic datum), October 1957, Army Map Service.

*Deposition rate of micrometeoritic materials* (as a means of dating oceanic sediments) at intervals from August 1957 to January 1960, Hawaii Institute of Geophysics, Hans Pettersson [23].

*Rubber cracking* (as related to ozone concentration at MLO and Hilo), April 1961, Robert A. Taft Sanitary Engineering Center, James P. Lodge.

*Total hemispherical radiation in spectral bands, surface ozone, number and size of dust particles at MLO and at its Hilo station* (to evaluate effects on materiel), January 1961 to July 1962, U.S. Army Electronics Proving Ground, Fort Huachuca.

*Collection of radiocarbon from nuclear tests*, February 1962 to present, Lamont Geological Observatory, Columbia University, Wallace Broecker.

*High-altitude sodium vapor cloud observations* (by photographic triangulation), May 1962 and intermittently to present, Sandia Corporation.

*Strontium-90 content of orographic rainfall* (at MLO and on the slopes of Mauna Loa), April 1963 and at intervals to present, Hazleton Nuclear Science Corporation, Paul Kruger.

*Fission products* (by air filtration), since August 1957, Atomic Energy Commission, John Harley.

### 4. MAJOR LONG-TERM PROGRAMS

Major continuing programs at Mauna Loa Observatory include surface and total ozone, carbon dioxide, solar radiation, ice nucleus counts, infrared hygrometry, and cognate observations and studies in weather and climate for the meteorological documentation and interpretation of the other data. An extensive project in atmospheric electricity was recently completed [6]. The present paper can do no more than touch upon a few highlights in each of these. Further information on instruments, procedures, and data may be obtained from the references or the authors.



## METEOROLOGICAL OBSERVATIONS

Local weather is observed hourly between about 0600 and 1800 LST and autographic records are obtained of atmospheric pressure, temperature, relative and absolute humidity, wind speed and direction, rainfall, and sunshine. Time-lapse cloud photography is used at times to preserve the visual aspect of the weather. Additional meteorological data are available from Weather Bureau stations at Hilo, where temperature, humidity, and wind are sounded twice daily (0200 and 1400 LST) to altitudes of 30 km. or more, and at Honolulu, 210 mi. to the northwest, which prepares synoptic charts for sea level (4 times daily) and 500, 300, and 200 mb. (twice daily) for an area from western North America to eastern Asia and Australia.

## TOTAL OZONE

The Observatory's Dobson spectrophotometer (No. 63) is the highest permanent installation of its kind. The clarity of the overlying atmosphere (which on many days permits observations both morning and afternoon), the high altitude and small noon zenith angle (which yields low values of ozone path length) and the relatively small day-to-day ozone changes typical of the latitude have been described by Dobson and Normand [7] as making MLO ideal for instrument calibration and for the determination of the extraterrestrial constant ( $L_0$ ) and its possible changes with time.

Half-monthly means since observations began are shown in figure 10. The recurrent seasonal features are clearly displayed in the individual years and in the mean: a mid-winter minimum (late January to late February), the sharp rise (found in total ozone nearly everywhere) to a peak in late April to early June, and the summer plateau followed by a decline to the winter minimum.

Of interest also is the tendency in the more recent years for the annual maximum to become progressively higher and more sharply peaked and to occur earlier in the year; so that while 1958 looked typically tropical, the years since then have become increasingly less so. The relationship of this trend to changes in the general circulation and to the sunspot cycle, as suggested by Willett [35], is being looked into.

The lowest half-monthly mean of record was 0.226 cm. in January 1961, and the highest 0.307 cm. in April 1963. Lowest and highest individual observations were 0.216 and 0.325 cm., respectively. (Vigroux coefficients are used throughout.)

The mean annual range has varied from 0.039 cm. (1958) to 0.076 cm. (1962): an amplitude which, while small, is—like the amount of ozone itself—high for the latitude.

Umkehr measurements (Method B) made on several days in July 1959 indicated an ozone maximum of about 0.019 cm./km. at approximately 28 km. [33].

## SURFACE OZONE

The ozone content of the air at Mauna Loa Observatory

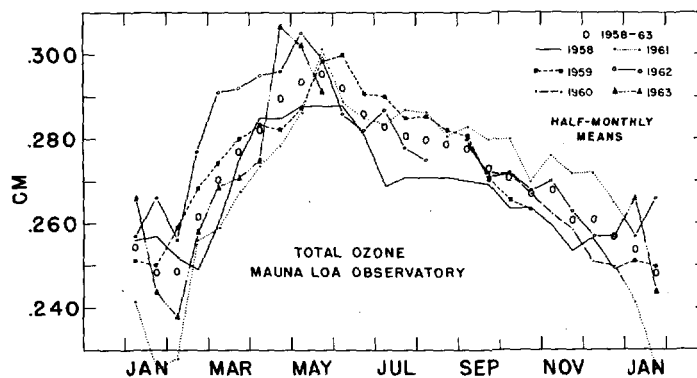


FIGURE 10.—Annual variation of total ozone at Mauna Loa Observatory, January 1958–May 1963. The principal features recur in each year, but maxima since 1959 have tended to peak more sharply and earlier in the spring. More recent years are less “tropical” in appearance than earlier ones.

has been monitored since August 1957 using, successively, an automatic chemical analyzer developed by Regener [29], a later version of the same instrument, and a MAST analyzer (Model 724-1). Ozone concentrations during that time have ranged from near zero to a maximum of well under 10 parts per hundred million (pphm) by volume. The long-term mean appears to be near 3 pphm.

Typically, surface ozone at Mauna Loa is high during the night and early morning and lowest in mid-afternoon. This diurnal cycle at times so closely parallels the mountain circulation (fig. 11) as virtually to force the inference that the nocturnal maximum represents the ozone content of the free air near MLO, and the afternoon minimum the influx from lower elevations of air whose ozone had been depleted during ascent or by prior residency beneath the inversion [21]. Changes may also be associated with synoptic events. One of the most remarkable (in mid-February 1958) accompanied the interruption of the trade regime by strong westerlies around a deep Low far to the north. On that occasion surface ozone rose within hours to twice its initial value, remained high for weeks, and then fell abruptly to its former level (fig. 12). The diurnal cycle survived the synoptic transitions, although it was less prominent during the cyclonic period, when cloud cover was greater and the mountain circulation correspondingly less intense.

Seasonally, surface ozone at MLO roughly parallels total ozone, with a maximum of about 5 pphm in spring and a minimum near 2 pphm in winter. Junge [15] finds the seasonal trend of daily ozone maxima at the Observatory consistent with global tropospheric ozone variations.

From about January 1961 to July 1962, MAST ozone analyzers were in use at both Mauna Loa and Hilo. The mean diurnal variations, shown in figure 13 for April 1962, a representative month, are strikingly out of phase. That at MLO has the nocturnal maximum and deep afternoon decline previously described, while Hilo's with its high

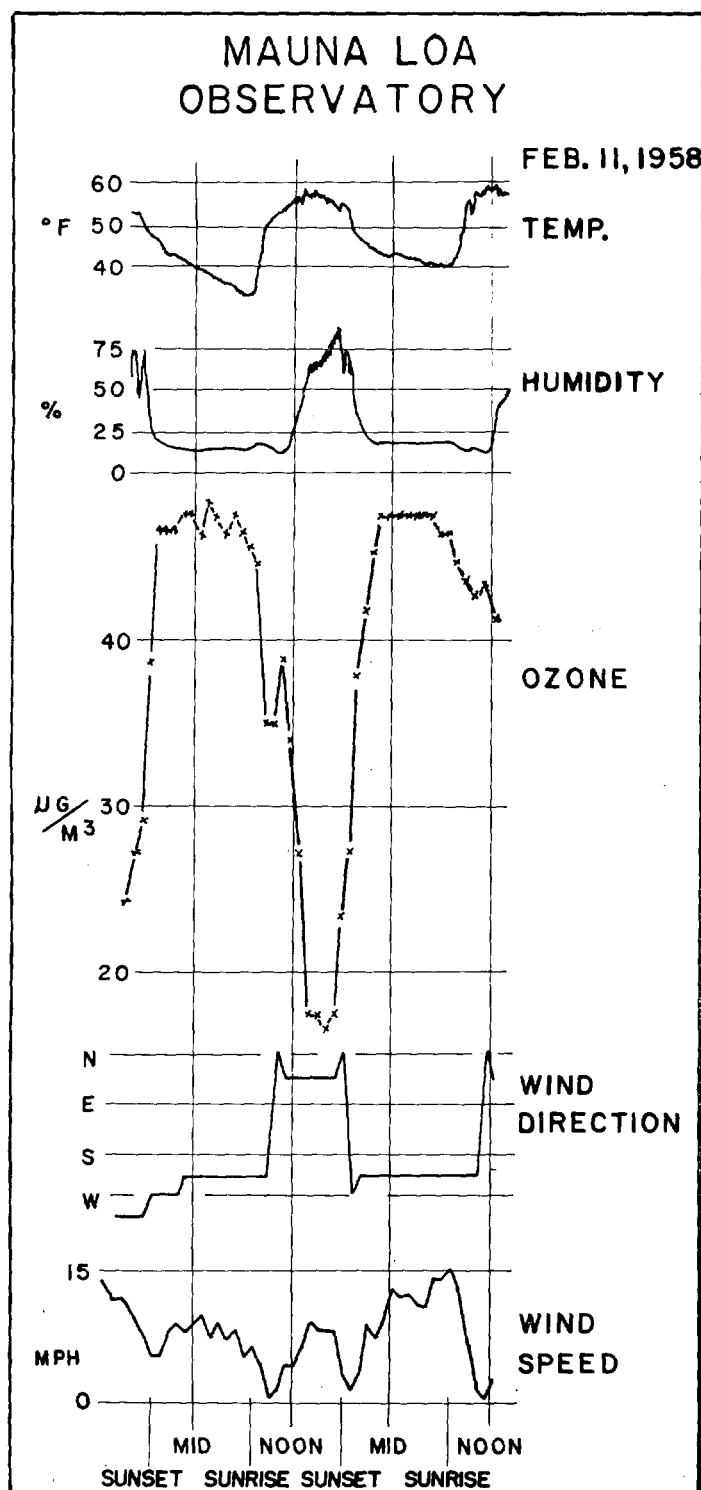


FIGURE 11.—Diurnal variation of surface ozone and selected meteorological elements, Mauna Loa Observatory, February 11, 1958. An exceptionally clear, but not an atypical, example of parallel variation, illustrating the relation between the daily oscillation of surface ozone and the mountain circulation.

daytime plateau and low nighttime values is typical for a locality without significant local photochemical production of oxidant and resembles the diurnal variation originally

attributed by Auer [2] to the destruction of ozone in the stagnant surface layer at night, and its replacement during the day by undepleted air brought down from aloft by convection and turbulence.

While it would be tempting to regard the similarity of the mean midday values at Hilo and Mauna Loa as arising from mixing, a close study of individual days suggests that ozone variations at the two sites are largely independent.<sup>2</sup>

#### CARBON DIOXIDE

The implications of a secular increase in the atmospheric carbon dioxide constitute a major cross-disciplinary problem in geophysics, but one which far transcends the interests of scientists alone. Measurements of  $\text{CO}_2$  began at MLO in March 1958 and are being carried on in closest collaboration with C. D. Keeling (Scripps Institution of Oceanography), who supplies the reference tanks of the gas and performs the final evaluation of the data. The past five years comprise the longest record of its kind and have made Mauna Loa a key station in the worldwide investigation of the carbon dioxide problem.

The instrument employed is a non-dispersive infrared analyzer [1], which continuously monitors air drawn through intakes mounted on four 20-ft. towers approximately 450 to 500 ft. distant and in mutually perpendicular directions from the main observatory building. Sampling and data processing are painstakingly done to detect and eliminate from the record possible contamination from the Observatory or by seepage from the mountain itself. Flask samples are also taken twice monthly at Mauna Loa and Hilo and at intervals by aircraft in the Hawaiian area. A full account of the program and the observational results is available in [22].

Diurnal, seasonal, and longer-term variations in carbon dioxide are to be found in the Mauna Loa data. Carbon dioxide is high during the night and forenoon, but evinces an afternoon decline (in a manner reminiscent of surface ozone) which Keeling ascribes principally to its depletion by vegetation in air moving upslope over the dense rain forests of the lower mountain.

A pronounced seasonal oscillation of about 6 ppm is also present in the Mauna Loa data (fig. 14). This is held to reflect the use and release of carbon dioxide on a hemispherical scale, presumably in response to the seasonal vegetative cycle.

Perhaps of paramount importance is the emergence from the Mauna Loa record of a steady rise in carbon dioxide since observations began there five years ago (fig. 15). The increase averages 0.7 ppm annually, which, as Keeling points out, is about half the rate at which carbon dioxide is currently being released to the atmosphere by the consumption of fossil fuels. However, since the ascending trend is superimposed on a seasonal

<sup>2</sup> The lack of calibration standards for surface ozone analyzers, the difficulty of getting any two of them to agree closely in ozone levels and variations, and the general uncertainty of measurements at such very low concentrations leave the authors with some reservations concerning their (and similar) data.

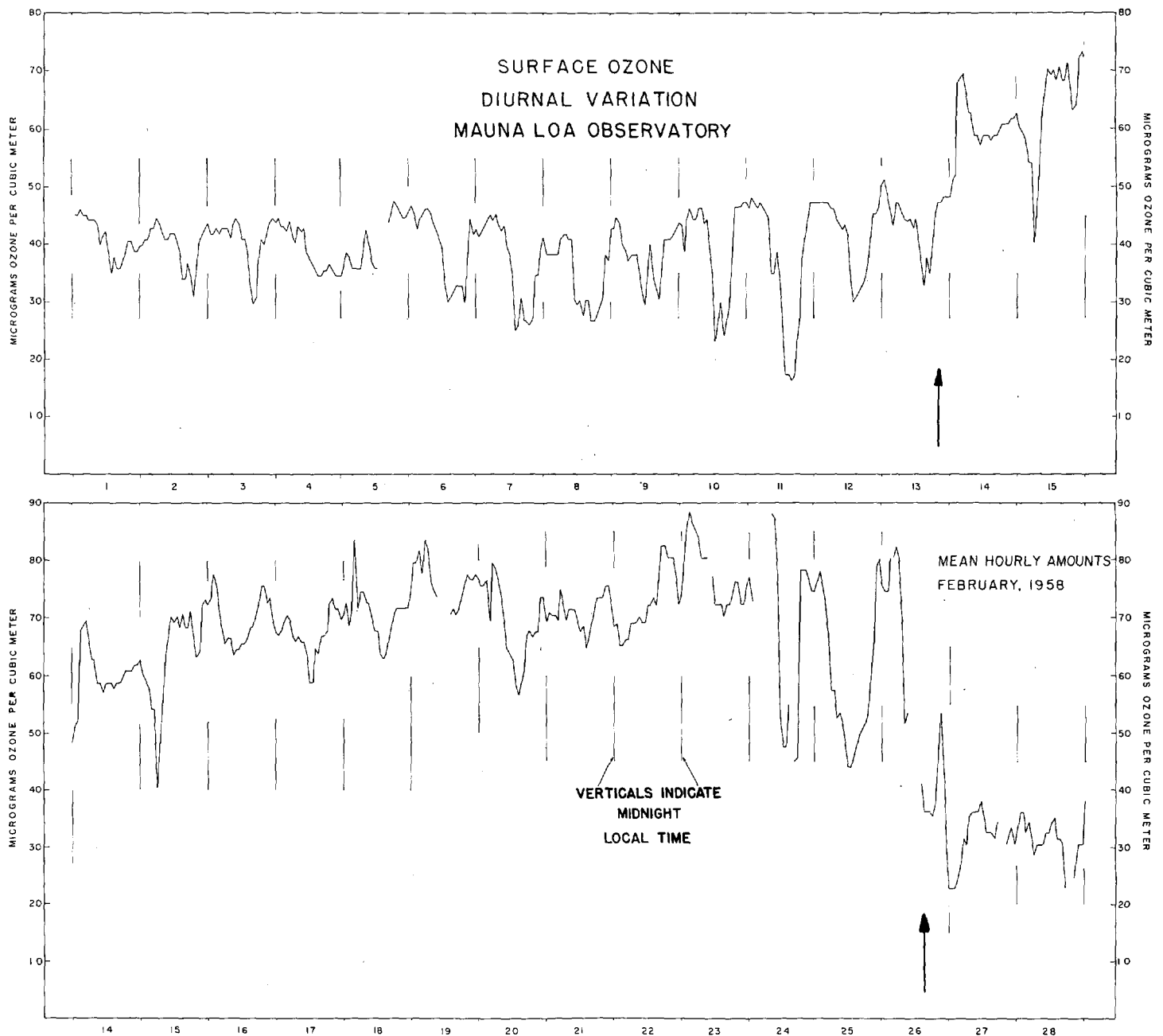
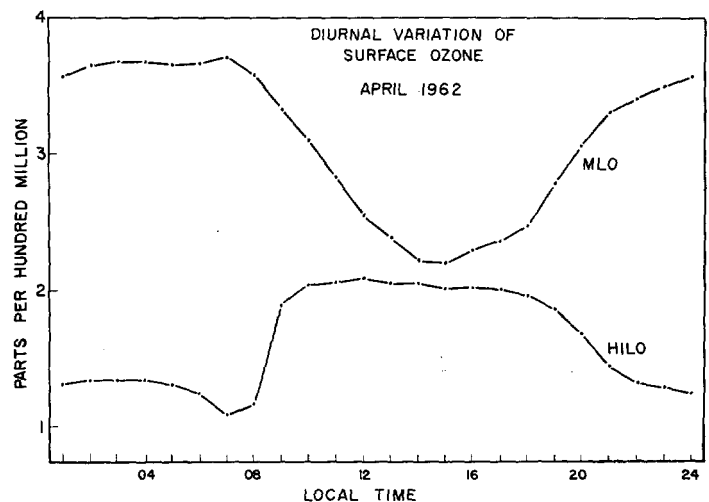


FIGURE 12.—This sharp rise and decline in surface ozone at Mauna Loa Observatory in February 1958 (see arrows), marked the interruption of the trades by a cyclonic regime. The diurnal ozone variation persisted throughout, but was less prominent during the cyclonic phase, when increased cloudiness inhibited development of the mountain circulation.

FIGURE 13.—Mean diurnal variation of surface ozone at Mauna Loa Observatory and Hilo, Hawaii, April 1962. Mauna Loa exhibits the afternoon minimum found there in most months. The curve for Hilo resembles that for other nonindustrialized localities without local photochemical production of oxidants.



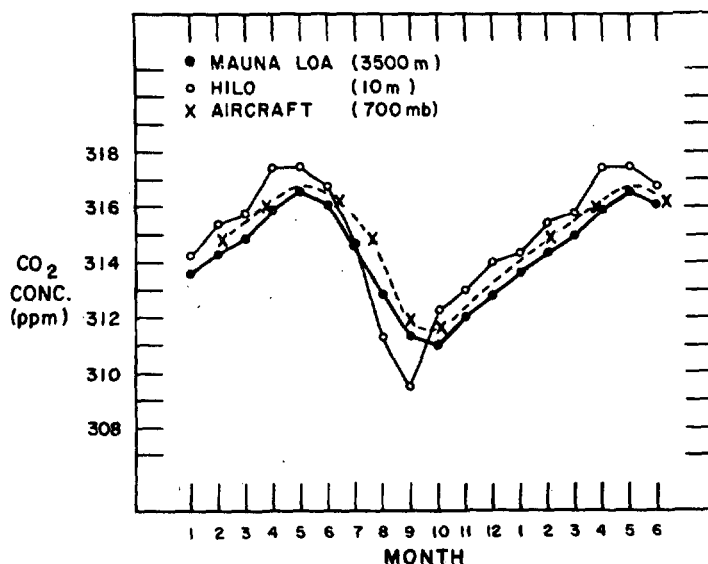


FIGURE 14.—Mean monthly concentration of  $\text{CO}_2$  at Mauna Loa Observatory, at Hilo, and at 700 mb. near Hawaii (from [22]). The seasonal oscillation is believed to reflect the hemispherical release and uptake of carbon dioxide.

oscillation of much larger amplitude and derived from but a few years of record, it can not be regarded as definitive until supported by further years of data.

#### ATMOSPHERIC ELECTRICITY

From September 1960 through August 1961 continuous and simultaneous measurements of the vertical potential gradient, the positive and negative electrical conductivity, the positive and negative small ion density, the rate of ionization, the air-earth current, and the positive or negative large ion density were made at MLO.

The principal purpose of the program was to obtain a quantitative index of the present atmospheric load of particulate matter as a bench mark with which future measurements of the same kind and at the same place might be compared and secular changes detected.

On Mauna Loa, as at other mountain stations where similar observations have been made, the atmospheric electric variables respond to local as well as to global influences. Nevertheless, the normalized diurnal variation (by universal time) of the air-earth current at Mauna Loa closely parallels the Carnegie observations (of October and November 1929) and the worldwide thunderstorm activity curve.

Mean hourly values of the atmospheric electric variables for the year of record are shown in figure 16. A complete account of instrumentation, procedures, and data has been given by Cobb and Phillips [6].

#### ICE NUCLEUS COUNTS

Present interest in the nature, number, and origin of the atmospheric ice-forming nuclei stems initially from

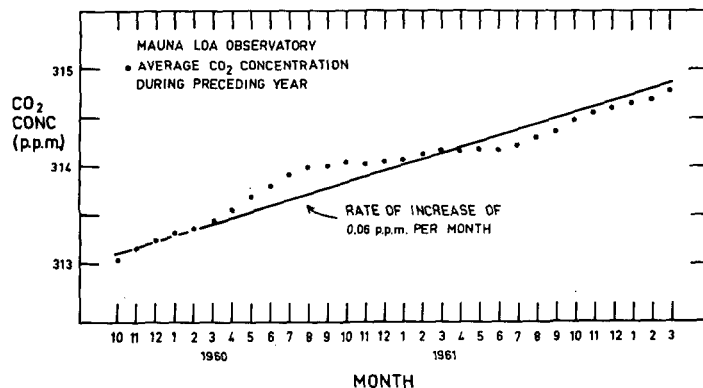


FIGURE 15.— $\text{CO}_2$  at Mauna Loa Observatory has increased annually by about 0.7 parts per million since observations began in 1958 (from [22]). The oscillation of values about the trend line arises from minor variations in the seasonality of individual years.

their possible involvement in precipitation processes of the Bergeron-Findeison type, but has been restimulated recently by hypotheses relating singularities in rainfall, ice nucleus concentrations, and other geophysical events to the prior injection of meteoritic material into the high atmosphere (for recent summaries see [3] and [8]).

Morning and afternoon ice nucleus counts using Bigg-Warner expansion chambers [34], as modified by the U.S. Weather Bureau [20], have been made at Mauna Loa since December 1957 and for intervals ranging in length from several weeks to a year or more [9, 18]. The Observatory averages fewer than one ice-forming nucleus per liter at  $-24^\circ \text{C}$ ., a background comparable with that found in mid-ocean and in regions remote from contamination [4, 5]; and ranges well below that at Hilo, itself a relatively isolated locality (fig. 17).<sup>3</sup>

Occasional peaks exceeding background values by an order of magnitude or more occur at Mauna Loa and Hilo (as they do wherever similar observations have been made); and there is some evidence for co-variation between the atmospheric ice nucleus content at the two sites [27].

Median morning and afternoon counts at Mauna Loa for October 1959 to December 1960 are shown in figure 18. Ice nucleus levels appear to be lower in winter and (although a gap in the record makes this less certain) afternoon counts exceed morning counts most conspicuously in summer. That the latter may reflect again the greater intensity in summer of insolation and hence of the thermally-induced influx of turbid sub-inversion air, is supported by Kline's finding [17] in January 1961 that counts made later in the afternoon than the usual time of observation tended to be substantially higher than morning counts.

<sup>3</sup> These counts are uncorrected for instrumental differences. Comparisons made by Kline [17] indicate that, relative to the Hilo instrument, the counts at MLO may be lower than (about half) those given in this paper.

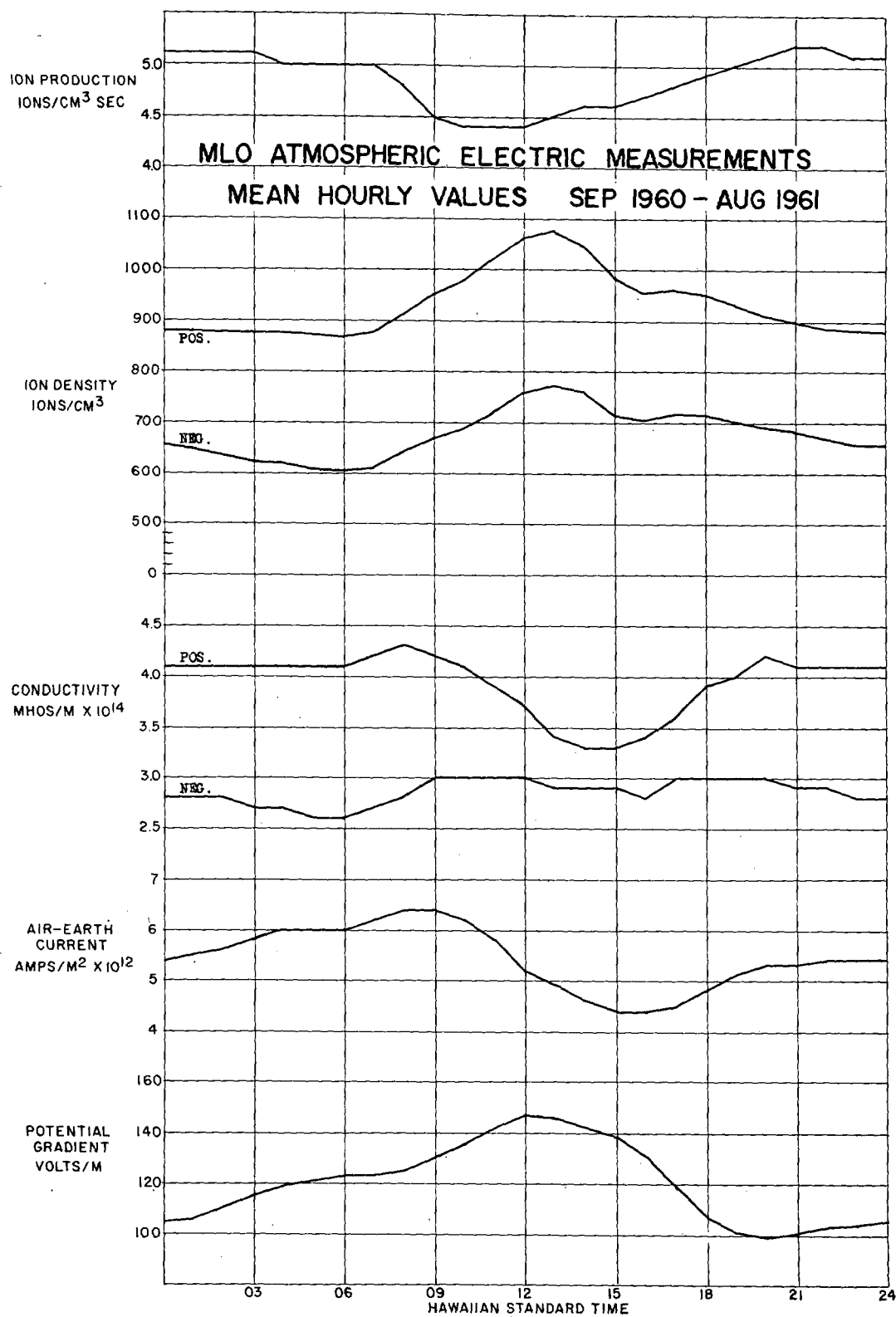


FIGURE 16.—Annual mean hourly values of the atmospheric electric variables at Mauna Loa Observatory, September 1, 1960–August 31, 1961 (from [6]).



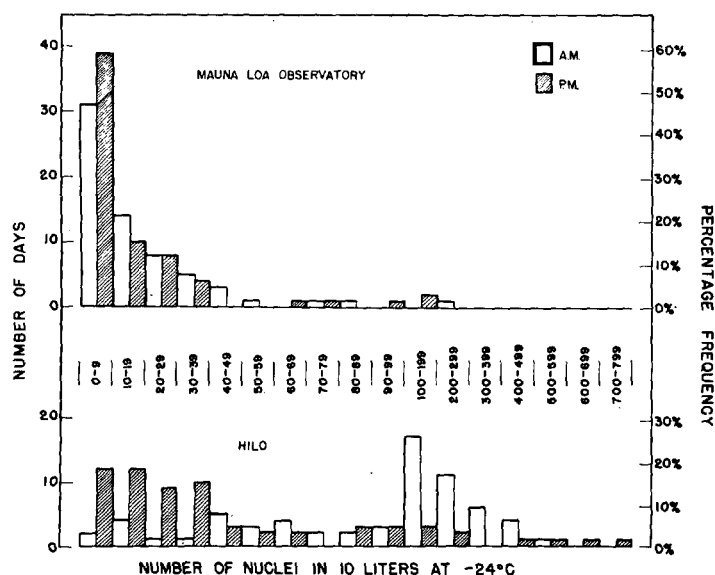


FIGURE 17.—Ice nucleus concentrations at Mauna Loa Observatory and at Hilo, morning and afternoon, from December 1, 1961–February 5, 1962 (from [27]). The background count at MLO is lower and peaks are fewer than at Hilo.

Volcanic eruptions which occurred within 50 mi. of MLO from November 1959 to February 1960 provided a rare opportunity to compare ice nucleus concentrations within the visible effluent with those made in the clear air at the same place and often on the same day. In contrast to the as much as 40-fold increase in ice nuclei reported by Osono et al. [14] during volcanic eruptions in Japan, counts at Mauna Loa were no higher within the effluent than outside it [25].

#### SOLAR RADIATION

Solar radiation has been measured at Mauna Loa Observatory since November 1957 by means of continuously recording Eppley horizontal incidence and normal incidence (10-junction) pyranometers. Filters (Nos. OG-1, RG-2, and RG-8) are employed at intervals with the normal incidence pyrliometer to obtain estimates of the turbidity coefficient. Until 1958 Beckman and Whitley (Gier and Dunkle) total hemispherical and net exchange radiometers were also in use.

In March 1961 and until July 1962, as part of an investigation by the U.S. Army Quartermaster Research and Engineering Command of the heat and radiation loads on men and materiel at a mountain station, and the atmospheric attenuation of these effects, a set of four new Eppley temperature-cosine error compensated radiometers equipped with Schott filters WG-7, OG-1, RG-2, and RG-8 were placed at MLO, and an identical set at the Observatory's Hilo office. Simultaneous hourly and daily totals (in langley) of solar radiant energy in each spectral band on a horizontal surface were recorded

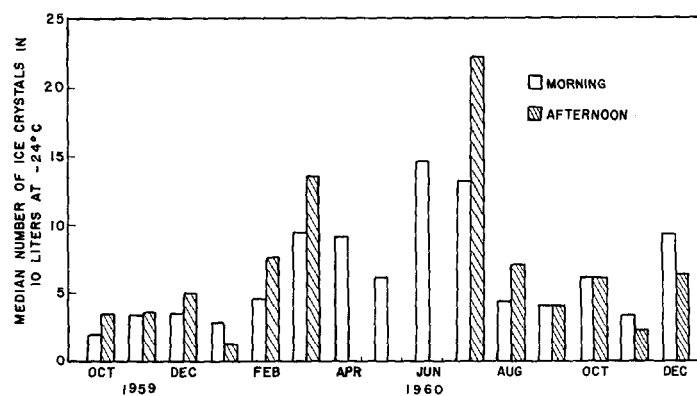


FIGURE 18.—Median monthly ice nucleus counts at Mauna Loa Observatory, October 1959–December 1960. The excess of afternoon over morning concentrations appears to be more pronounced in the warmer half-year, and may reflect the earlier onset and greater intensity of the upslope flow in that season.

continuously. All the data have been punched on IBM cards and are awaiting climatic and physical analysis.

The outstanding characteristics of solar radiation at Mauna Loa are its high intensity and the large number of clear days and hours. On clear days at solar noon normal incidence radiation at times exceeds  $1.70 \text{ ly. min.}^{-1}$ , approximately 85 percent of the solar constant. The normal and horizontal incidence traces on a typical sunny day are shown in figure 19. When corrected for altitude and solar distance, the mean and maximum intensities of normal incidence radiation on clear days at Mauna Loa exceed those at Little America by about 3 and 6 percent, respectively, and are nearly identical with values at the South Pole Station (despite the atmospheric water vapor deficit in the Antarctic). This extraordinary clarity of the atmosphere above Mauna Loa Observatory is confirmed by turbidity computations for the same and other localities [13].

#### 4. IN PROSPECT

It is doubtful that the man to whom this volume and this paper are dedicated would have been pleased with an account which looked only to the past of the mountain station in which he saw such promise, and said nothing of its future. The authors share this view.

Many things lie ahead for Mauna Loa Observatory. For some of these, time or means have hitherto been lacking. For others an intensified effort is planned. Still others represent the Observatory's expanding role as a center for atmospheric studies.

Radon-daughter measurements are to begin, to determine local levels and variations.

In total ozone, Umkehr observations will be made concurrently with ozone-soundings from Hilo, to help define the vertical distribution of ozone in the subtropical

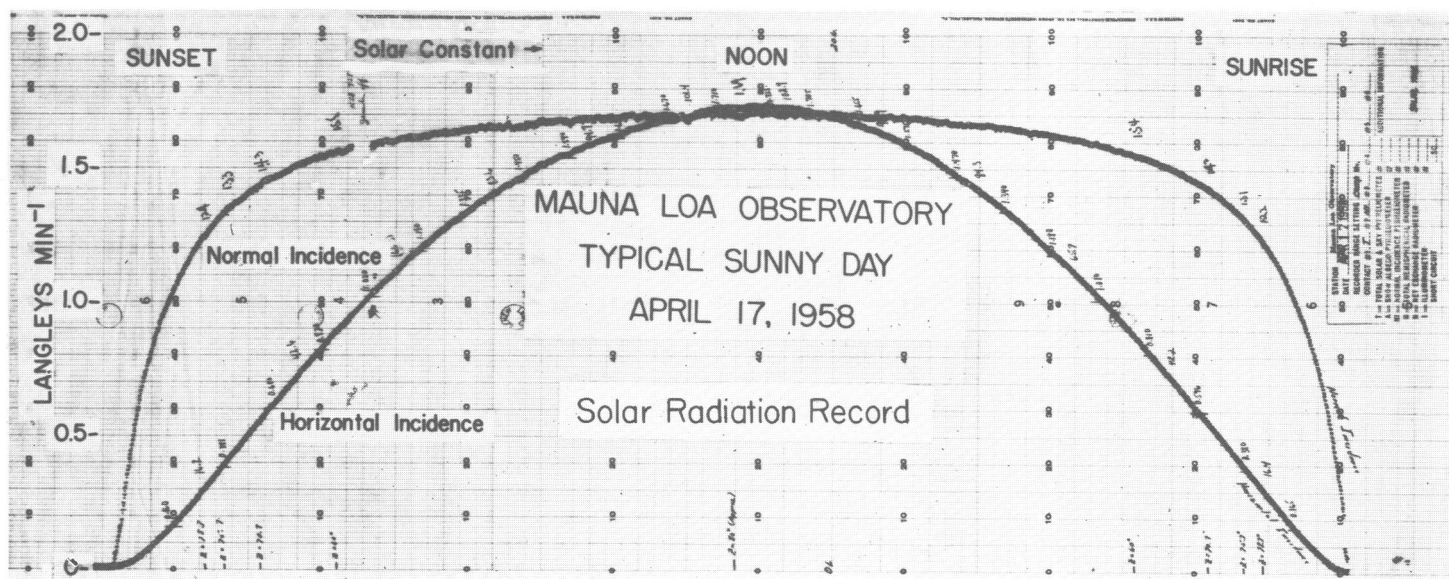


FIGURE 19.—Normal and horizontal incidence solar radiation at Mauna Loa Observatory on a typical clear day. The intensity of normal incidence radiation at solar noon sometimes exceeds  $1.70 \text{ ly. min.}^{-1}$ , about 85 percent of the solar constant.

Pacific. After extensive calibration checks, the Mauna Loa Observatory Dobson is to be employed to estimate the extraterrestrial constant and its time variations.

A major investigation of the composition, properties, and dispersion of gaseous and particulate effluents during the next volcanic eruption in Hawaii has been organized by Mauna Loa Observatory in collaboration with the National Center for Atmospheric Research, the Hawaii Institute of Geophysics, and other groups.

The properties and motions of the atmospheric envelope adjoining Mauna Loa will continue to receive close attention as a key to interpreting the observations made within it. Portable stations already in use at several points on the mountain will be moved from place to place throughout the year to map out the distribution of wind, temperature, and humidity in the vicinity of the Observatory. These observations will be augmented at intervals by air trajectory studies using zero-lift and constant-pressure balloons and tracer materials. Radiosondes modified for slow ascent and wiresonde use will be released from the lower slopes to delineate the location and structure of the trade inversion contiguous to the mountain. Infrared hygrometry with an improved instrument will help define in greater detail the extended periods of exceedingly low humidities at Mauna Loa and the transitions between the upslope and downslope branches of the mountain circulation.

Also within the surface layer the vertical profile of carbon dioxide and its changes under various meteorological conditions is to be looked into by sampling through intakes mounted at intervals on a 50-ft. tower at Mauna Loa; and traverses of  $\text{CO}_2$  and surface ozone will be made along the slopes, particularly in the rain forest and through

the inversion, to check current explanations of the diurnal variation in both those elements.

There are other things in MLO's future. It is certain that the Observatory will continue to attract projects as numerous and diverse as those listed earlier in this report. The tremendous spurt in the space-oriented disciplines, and a concomitant interest in high-altitude stations for astronomical and other purposes, is directing increased attention to MLO itself and to its possible use as a base for work done at Mauna Loa summit, 2500 ft. higher.

But perhaps more valuable than any of these endeavors, actual or potential, is the Observatory's role as a benchmark station. With the continuing industrialization of the planet and the increasing atmospheric load of a variety of gaseous and particulate contaminants, the existence within a stable local environment of such a vantage point from which to calibrate the free atmosphere is of inestimable value. Thus, observations during the International Quiet Sun Year will be compared with those made when MLO began, at the height of the solar cycle.

But beyond that time Mauna Loa Observatory will continue to regard as its primary responsibility the careful and uninterrupted surveillance of carbon dioxide, solar radiation, total and tropospheric ozone and, at intervals, the atmospheric electric variables—the significant indices of global atmospheric change.

#### ACKNOWLEDGMENTS

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